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The Medical and Human Performance Problems of Living Under the Sea

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Recent undersea experiments in the United States and France showed that divers can live and work effectively for many days from dwellings placed on the continental shelf to depths down to 432 feet. If prolonged exposure to the hostile underwater environment is to be tolerated successfully, existing physical, biological and equipment hazards must be recognized, prepared for and, when possible, circumvented.

Les récentes expériences sous-marines entreprises aux Etats-Unis et en France ont permis de montrer que des plongeurs peuvent vivre et travailler efficacement pendant plusieurs jours dans des demeures aménagées dans le plateau continental à des profondeurs pouvant atteindre 432 pieds. S'il s'avère qu'une vie prolongée dans le milieu sous-marin hostile peut être couronée de succès, il importe de définir les risques existants sur les plans physique, biologique et mécanique (appareillage), de s'y préparer et, si possible, de les prévenir.

MAN is just beginning to realize the extent of the scientific, military, and economic potential which awaits him beneath the surface of the world's oceans. In recent years there has been a sudden surge of enthusiasm for the recovery of the natural resources which have existed in the sea for countless millennia. This interest has been supported by widespread military activity in such development areas as underwater defence systems and submersibles, and submarine rescue. Also, great stimulation has been provided by scientific, salvage, construction, and archeological undersea efforts.

To unlock this inherent undersea potential, man must descend beneath the waves and expose himself to the hazards of a new environment. Man has been diving for centuries, but only recently has he been able to dive deep, and to live under the sea for prolonged periods.

Recent diving expeditions to the depths of the continental shelf off the United States and France have brought into focus the potential medical and human performance problems associated with living for extended periods deep beneath the sea (Table I).

In late June 1964 in the ocean near Great Stirrup Cay in the Bahamas, Robert Sténuit and Jon Lindbergh lived at 432 feet for 49 hours in an underwater house, designed by Edwin A. Link.[1-3] This was the second phase of Link's "Man in Sea" project, and it demonstrated that man could dive, work and live under the conditions of the deep continental shelf.* However, during decompression from this deep-pressure exposure Sténuit developed mild decompression sickness and had to be treated by recompression and hyperbaric oxygen.

In July of the same year, four U.S. Navy "aquanauts" of the "Sea Lab I" project lived for 11 days 193 feet below the surface of a restless ocean near Bermuda.[1, 5, 6] Their stay at this depth was not without hazard, for one diver came close to death when his breathing apparatus did not function properly.

In September 1965, six men of J.-Y. Cousteau's undersea research group lived and worked from a dwelling for almost 22 days 330 feet below the sea.[1, 7] At this depth the divers apparently had no medical problems except mild discomfort in the large joints.[8]

In the same month, in the U.S. Navy "Sea Lab II" project, three teams of 10 men each successfully lived and worked for 15 days at 205 feet beneath the cold, murky waters off the California coast.[1, 9] One diver, astronaut-aquanaut Scott Carpenter, received puncture wounds in his right index finger from the toxic spines of a scorpion fish. Because of the toxicity and excruciating pain he was given cortisone, antihistamines and analgesics.[10] During decompression from this dive, one of the aquanauts developed decompression sickness, and was successfully treated by recompression.

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*It is noteworthy that 432 feet is the average depth of the world's continental shelf-edge before it drops into the downward steepness of the continental slope.[4]

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TABLE I.—CHRONOLOGICAL DEVELOPMENT OF SATURATION DIVING
(INCLUDES DRY CHAMBER EXPERIMENTATION AND FRESH AND SALT WATER SUBMERGENCE)

Date	*Sponsor*	*Project name*	*Depth (feet of sea-water)*	*Duration*	*Location*	*Dwelling type*	*Divers*	*Breathing gas*
1962 Sept.	E. A. Link	Man in Sea I	200	24 hours	Villefranche, Mediterranean Sea	Link cylinder, aluminum, 3 x 10 ft.	Sténuit	3% O_2 97% He
Sept.	J.-Y. Cousteau—OFRS	Conshelf I	35	7 days	Marseille, Mediterranean Sea	"Diogene", 8 x 16 ft. cylinder	Falco, Wesly	Air
1963 April	Capt. G. F. Bond, U.S. Navy	Genesis (D)	150	6 days	Naval Medical Research Laboratory (NMRL), Bethesda, Md.	Dry chamber	Barth, Lavoie, Fisher	O_2, He
July	J.-Y. Cousteau—OFRS	Conshelf II	33	1 month	Shaab-Rumi Reef, Red Sea	"Star House" 4 x 8 ft. diam. cyl. in star configuration	Falco, Gilbert, Vaissiere, Vanoni, Wesly	Air
			85	7 days	Shaab-Rumi Reef, Red Sea	"Deep House" 7.5 x 16 ft. vertical cylinder	Kientzy, Portelatine	Air, He
Aug.	Capt. G. F. Bond, U.S. Navy	Genesis (E)	200	12 days	NMRL, New London, Conn.	Dry chamber	Barth, Bull, Manning	3.5% O_2 6% N_2 90.5% He
Dec.	U.S. Navy	Linear ascent from saturation in oxygenhelium	300	24 hours	Experimental Diving Unit (EDU) Washington	Dry chamber	Kosimaki, Simeone	O_2, He
1964 Feb.	U.S. Navy		300	24 hours	EDU Washington	Dry chamber	2 divers	O_2, He
March	U.S. Navy		400	24 hours	EDU Washington	Dry chamber	Kennedy, Zuber	O_2, He
June	E. A. Link	Man in Sea II	432	48 hours	Great Stirrup Cay, Bahamas	SPID (submersible portable inflatable dwelling) 8 x 4 ft. rubber tent	Lindbergh, Sténuit	4% O_2 96% He
July	U.S. Navy	Sea Lab I	193	11 days	Argus Island, Bermuda	"Sea Lab I", 40 x 9 ft. cylinder	Anderson, Barth, Manning, Thompson	16% N_2 4% O_2 80% He
1965 Feb.	Ocean Systems, Inc.	Man in Sea	450	24 hours	Tonawanda, N.Y.	Dry chamber	Noble, Sténuit	3% O_2 97% He
Aug.	Ocean Systems, Inc.	Man in Sea	650	48 hours	Tonawanda. N.Y.	Dry chamber	Christensen, Noble	1.5% O_2 98.5% He
Sept.	U.S. Navy	Sea Lab II	205	45 days	La Jolla, Calif.	"Sea Lab II", 57 x 12 ft. cylinder	28 USN, NASA and civilian scientist divers	4% O_2 16% N_2 80% He
Sept.	J.-Y. Cousteau—OFRS	Conshelf III	330	22 days	Villefranche, Mediterranean Sea	Sphere, 20 ft.	6 divers	2% O_2 0.5% N_2 97.5% He
Nov.	Westinghouse-Marine contractors	Smith Mt. Dam project	190	40 days	Smith Mt., Va.	Surface deck chamber	2 teams of 4 divers	

In past experiments, living under the sea has involved the three-chamber concept. The most important of the chambers is the undersea dwelling in which the divers live. Resting on the ocean floor, it contains a gaseous environment at a pressure equivalent to the ambient water pressure. This enables the divers to carry out sorties into the surrounding waters and to return to a dry, comfortable base. After the work on the ocean floor is completed, the divers transfer from the dwelling into a submersible decompression chamber. This chamber transports them to the surface of the sea, while holding them at bottom pressure. At sea level they transfer again, this time to a deck decompression chamber on the surface support ship. Here, under the watchful eyes of the "life-support" team, decompression that frequently lasts several days is carried out.

The medical and physiological problems of prolonged deep "saturation" diving* include all of those encountered in short-duration dives. These problems have been discussed extensively in the literature.[11-22]

However, because of the extended depths and times of saturation dives, many medical and human performance problems, unique to this type of exposure, may arise. This paper will describe briefly the most significant aspects of both the old and new problems as they relate to man's attempts to live under the sea.

PROBLEMS ARISING FROM THE ENVIRONMENT

The Physical Environment

The average depth of the oceans is 12,000 feet,[23] and the deepest recorded depth is about 35,800 feet in the Marianas "trench" near Guam.[24] However, the immediately available economic potential of the oceans is concentrated on the continental shelves,[25-27] an area nearly equal in size to the surface of Africa.[1, 28] These shelves average 300 feet in depth and they are rarely much deeper than 1000 feet. It is important then to concentrate manned diving efforts to all depths down to 1000 feet. However, to determine the significant adaptation, performance and reserve limits of the working diver, pressure-research studies must be done on man to depths greater than 1000 feet.

At 1000 feet the diver will be subject to a pressure of 460 lb./sq. in. absolute. The sea-water pres-

*"Saturation" diving is a relatively new term. It refers to dives made to a given depth for periods usually longer than 24 hours. A diver is said to be saturated when his tissues will absorb no further measurable quantities of inert gas. Once this saturation point is reached, the decompression period is essentially the same regardless of the duration at depth. Consequently the bottom-time/decompression ratio is much more efficient in saturation dives as compared to short-duration dives. For example: the short-duration diver must decompress after each day's dive. In a long job he spends considerably more time decompressing than he does working on the bottom. However, the reverse is true of a saturated diver. Once saturated, he can stay as long as he wishes at the bottom depth and, after the work is completed, can return to the surface after only one decompression.

sure of any dive, because of its direct and indirect effects on gases and tissues in the body, presents the greatest potential hazard to the diver; all other problems are usually related in some manner to the effect of pressure. Two serious direct pressure effects, recognized previously in short-duration dives, are otic barotrauma[14-17] and air embolism.[12, 14-17, 22, 29-32]

The temperature of the world's oceans varies between -2° C. and +30° C. (28.4° F. — 86° F.).[23] However, manned diving operations will probably be carried out in water well towards the lower middle of this range.[33] Work has shown that effective underwater performance requires diving suits which have a supplemental heat source as well as thermal insulation[33, 34] (Fig. 1). Even in shallow water, temperatures are usually in the range of 45-60° F. It is a well-known fact, emphasized in recent undersea-living experiments, that exposure to cold water rapidly and seriously decreases the diver's efficiency[34-37] and accentuates several other hazards.[38, 39] Several of the early deep saturation experimental dives were carried out in tropic seas because of the excellent visibility and warm water in these areas.

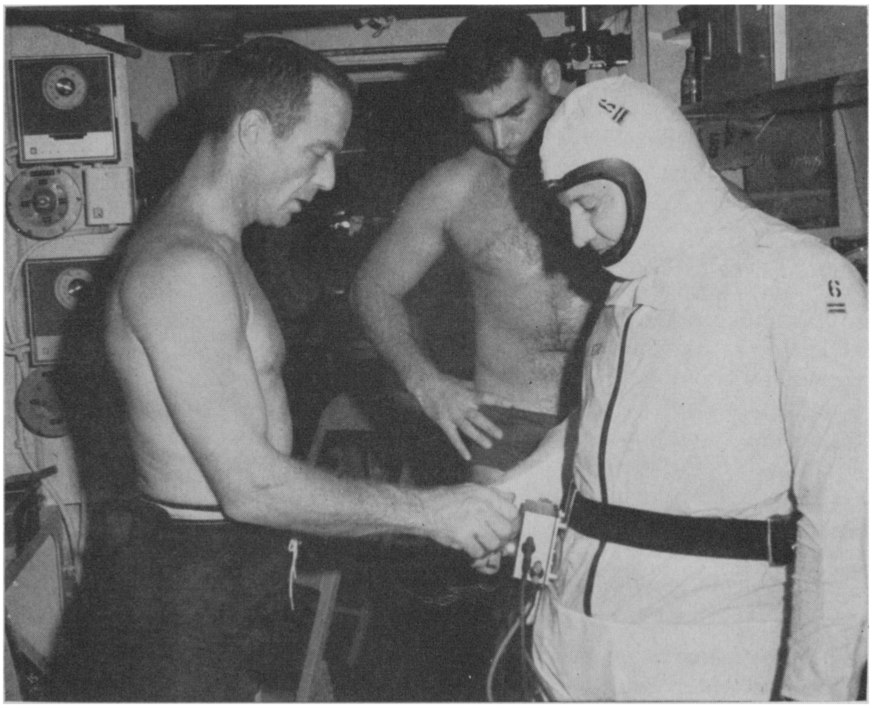

Fig. 1.—In Sea Lab II, 205 feet below the surface of the Pacific Ocean, team leader Cdr. M. Scott Carpenter USN (NASA) checks the controls on the electrically heated wet suit worn by aquanaut Fred Johler prior to an underwater sortie to test the suit. (Official photograph, U.S. Navy.)

Visibility in ocean waters can range from hundreds of feet in a clear tropic area to zero in certain locations. Clear water is the exception; the diver is usually limited to a few feet of visibility. Poor visibility reduces underwater maneuverability and work efficiency. A very real hazard of poor visibility is that it increases the diver's chance of fouling on man-made or natural obstructions.

The currents of the continental shelf are frequently strong and unpredictable, and a diver rarely works under "no current" conditions. Most men can work in currents of ½-1 knot. However, when the current reaches 3-4 knots, it becomes almost impossible to carry out any effective task other than observation. Under these conditions the diver is so busy maintaining his free-floating position that he is unable to do much effective work.

The composition and contours of the continental shelf sea bed vary from the flat mud bottom near the Mississippi delta to the craggy walls of Scripp's Canyon off California.[4, 23] Because the average slope of the shelf is about two fathoms per mile,[23] it is commonly pictured as a flat and monotonous place. On the contrary, the shelf has underwater ridges, boulder-strewn slopes, and deep rutted canyons.[4] These variations in the topography of the ocean floor pose potential hazards in the positioning and performance of the diver and his support equipment.

Serious potential physical dangers may develop in the relatively short time it takes the diver and his equipment to enter and leave the water. The transition of the suited diver or his support equipment (submersible decompression chamber, underwater dwelling) during the placement and retrieval phases should take only a few moments to accomplish under normal circumstances (Fig. 2). However, unpredictable environmental situations, such as high winds and sea states, often develop. Mechanical failure of placement and retrieval equipment can further complicate the picture. In any event, when heavy dynamic loads, including the diver, are transferred from the ship to the sea, and back, the potential hazard to the diver is high. If the loads are not kept from swinging or moving in relation to the vessel, the divers (or deck crew) may suffer severe impact trauma.

When the diver, or his equipment, is attached to the surface work-platform by an umbilical line containing his breathing gas, communication and power supply, he becomes subject to surface weather activity. The ship or barge must maintain a fixed position, otherwise the umbilical line will be subjected to dangerous tension stress. Decompression, which usually must proceed in exact depth-time stages, can be very hazardous if the diver and his line to the surface ship are subject to the rolling action of heavy seas.

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In many underwater tasks heavy loads may have to be placed at or removed from the underwater work site (Fig. 2). Particularly in waters of poor visibility, when heavy equipment is lowered from the surface ship (and hence is moving with it), the diver or his support equipment may be injured or damaged. It is therefore important to "uncouple", as soon as possible, the relative motions of the equipment being lowered and the diver receiving the equipment on the ocean floor.

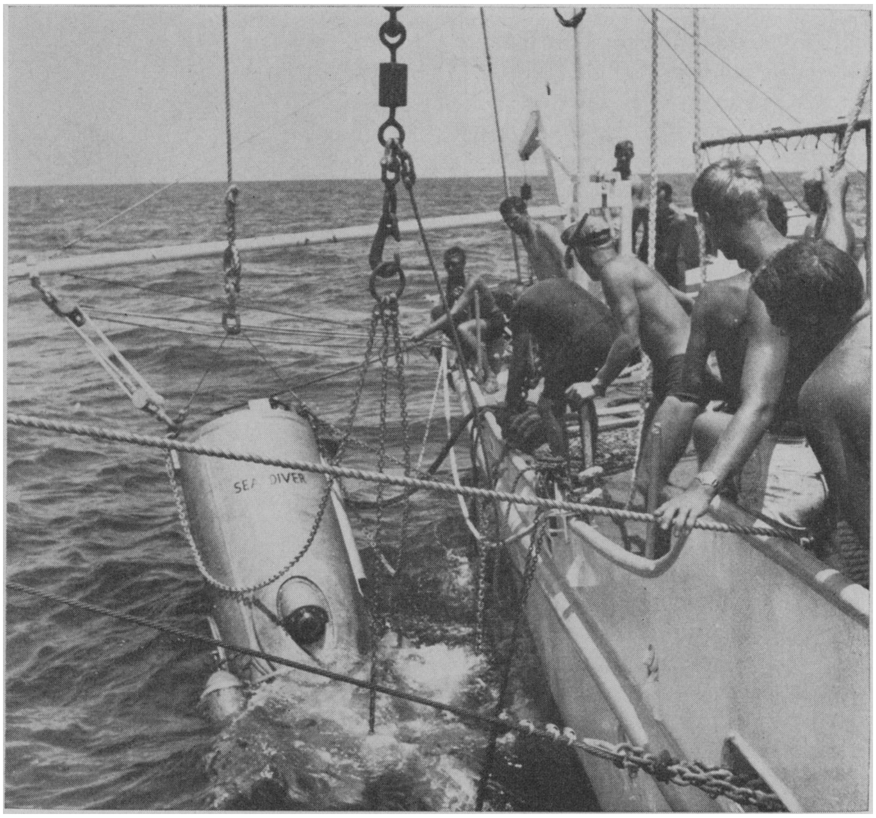

Fig. 2.—Ocean recovery of the Link submersible decompression chamber with divers aboard under pressure. This photograph was taken just prior to the Link "Man in Sea" phase II experiment in which two divers lived for 48 hours at 432 feet. (Photograph by R. P. Sténuit.)

The Marine Environment

Much has been written about the hazards of sharing the underwater world with certain creatures of the sea. Potential hazards for divers who live for long periods in dwellings on the ocean floor include marine organisms that range from unicellular bacteria to the unpredictable shark.[32, 40]

Sea water has such a rich variety of unicellular organisms that pathogenic bacteria or fungi may develop and multiply in the synthetic environments of future sea-dwellings. It is interesting to speculate what mutations may occur to allow specific organisms to adapt from sea life to that in a pressurized oxygen-inert gas mixture. It is even conceivable that certain of these organisms may cause new and serious infectious diseases in future divers. The respiratory and dermatological systems, and particularly the external ear,[9, 41] appear to be most vulnerable to infectious diseases when man is living under the sea, as they are exposed to constantly changing conditions of pressure, temperature, and humidity.

Tropical waters have their own spectrum of hazards. For example, coral lacerations decrease diver efficiency, not only because of the initial trauma, but because these wounds tend to become infected and take many weeks to heal.[40, 42] In both tropic and temperate waters, divers risk increased exposure to the poisonous barbs and spines of stingrays and scorpion fish (Fig. 3), as well as the painful stab of sea-urchin spines.[40, 43]

Divers frequently work around barnacled, or rusted, steel frames or structures. Lacerations, particularly of the hands, are a hazard common to all men working in such situations.[44] Not only do underwater abrasions and lacerations take longer to heal than those suffered in air, but such trauma may draw blood and lead to a shark attack.[32, 40, 45, 46]

Sharks are common to all oceans and particularly to the warm waters of the tropics.[47] Fortunately, however, few divers have reported unprovoked attacks.[48] It should be stressed that although there are many possible hazards from marine animals, the chance of a diver's incurring even one such hazard while he lives under the sea is slight.

However, the attitudes of the marine animals may change as the diver and his equipment become more or less permanent fixtures on the ocean floor. According to Sténuit,[3] Cousteau,[49] and Bond,[50] certain fish species (large groupers) were at first shy, and then became increasingly curious. Some fish, after exposure to the human divers, became definitely aggressive. It is interesting to speculate what the future relationship may be between the diver and unpredictable creatures such as the killer whales[51] and great white sharks.

Ultimately we hope that we can increase our knowledge of marine biology to the point where we can enlist certain marine animals as our allies in undersea activities. In recent U.S. Navy experiments a porpoise was trained to deliver messages 200 feet to the surface and to search and help recover "lost" divers[9] (Fig. 4). In future prolonged deep dives, man will have to give considerable

Fig. 3.—Aquanaut Ken Conda warily eyes a sculpin or scorpion fish near the conning tower of Sea Lab II. The fish were found in large numbers around the undersea habitat and one of them wounded Cdr. M. Scott Carpenter, USN (NASA). (Official U.S. Navy photograph.)

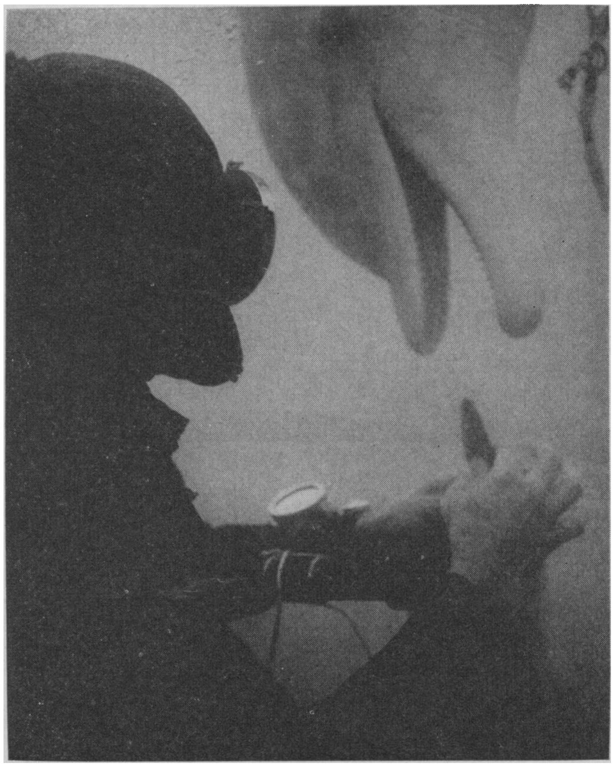

Fig. 4.—U.S. Navy diver John Reaves rewards porpoise Tuffy with a fish as they train together 80 feet down in the open ocean. A snap hook is attached to Tuffy's harness which enables him to carry messages and tools to the divers. (Official U.S. Navy photograph.)

thought to, and carefully control, his changing relationship with the natural inhabitants of the deep and shallow seas.

The Gaseous Environment

Man's success at working at continental shelf depths depends on his inhaling gases at a pressure equal to the surrounding water pressure. The selection, concentration and purity of these gases present specific problems, particularly with regard to the oxygen carrier or diluent. The question of the optimal tolerable partial pressure of oxygen (PO_2) in the breathing mixtures used beneath the sea is still under investigation.[1, 9, 38, 39, 41, 52] Sea-level experiments have shown that, for periods of several days, PO_2's of less than 100 mm. Hg and more than 400 mm. Hg may induce hypoxia and hyperoxia, respectively.[53] It has become evident that during a saturation dive it is unwise to attempt to maintain PO_2 at a sea-level equivalent of 160 mm. Hg. One reason for this is that reliable analysis and control devices for narrow oxygen ranges are not generally available. Another reason is that relatively low partial pressures of oxygen increase the time required for decompression. Due consideration must also be given to such factors as the duration of exposure, the diver's metabolic activity, requirements for muscular effort, inert-gas partial pressure, need for decompression and the specific phase of the "dive profile."* In undersea-living experiments to date, the PO_2 has been kept between 150 and 400 mm. Hg.[1, 5, 8, 9] During the latter phases of decompression, PO_2's of 1500 mm. Hg and greater are occasionally used.[1, 32, 49, 54]

There seems to be more general agreement about the optimal level of PCO_2. For dives of several days' duration, the PCO_2 should probably be maintained below 7 mm. Hg,[1, 55] although in sea-level experiments, man has adapted to a PCO_2 almost twice as high.[56, 57] It is most important that this gas, and others that make up the underwater environment, be accurately analyzed and controlled. Only in this way can the various potential toxicities be anticipated and prevented.

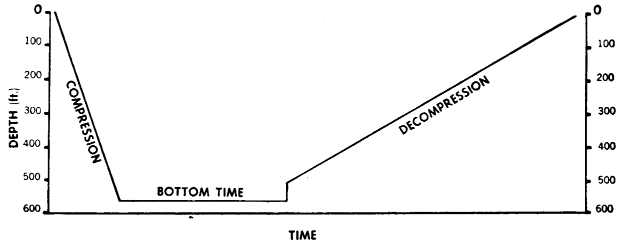

Fig. 5.—Schematic diagram of a dive profile showing the three major phases: compression, bottom time and decompression.

*A "dive profile" describes the three major phases of a dive (compression, bottom-time and decompression) in terms of a depth-time plot. It allows the diver and topside support team to know at what depth the diver should be at a given time, and *vice versa* (Fig. 5).

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In the atmosphere of the underwater habitation there are a large number of microcontaminants which, if allowed to build up, can become toxic.[1, 5, 6, 9, 89] It is an axiom of undersea living that the concentration, or toxic level, of most gases are directly proportional to the number of atmospheres of pressure in the breathing mixture. In other words, if a gas which exerts a partial pressure of 7.6 mm. Hg at sea level is compressed to 200 feet or seven atmospheres absolute, it would exert a partial pressure of seven times 7.6, that is 53.2 mm. Hg. If this calculation is applied to CO_2 it is apparent that, at 200 feet, breathing such a mixture would rapidly lead to hypercapnia. The design of any underwater dwelling, diver's breathing apparatus, or decompression chamber must take into consideration and exclude or remove all potential microcontaminants, such as volatile hydrocarbons and oil-base paints. It should be stressed that the possibility of microcontaminant build-up, such as carbon monoxide, increases with the length of a dive.

Any dwelling or chamber on the ocean floor has a hatch or opening that allows the diver to enter the sea. However, through this opening a great deal of water vapour (from the sea-water) also enters. Other sources of moisture are the diver's wet clothes, his skin and his metabolic processes. If these sources of water vapour are not controlled, humidity soon builds up to high levels and gives rise to problems that are proportional to the atmospheric temperature and to the length of exposure.[1] The immediate effect of humidity is to chill the diver and to make him uncomfortable. Everything he touches is wet, including his clothes and blankets, and the dampness can become intolerable. The general effect on the skin of constant exposure to 100% relative humidity is serious. It is similar to, although less serious than, the manifestations seen after prolonged water immersion. Several divers, after long underwater sorties, have reported softening of the skin, particularly of the palms.[41] This is usually accompanied by a wrinkling and whitening, and if this condition is allowed to continue, the diver becomes unable to work with his hands. The skin tears easily, and the hands become sensitive. In this condition the skin is much more susceptible to infection, and the healing of existing wounds is delayed.[58] To allow the diver to "dry off" effectively, and be comfortable after his daily periods of underwater work, all underwater dwellings must be provided with humidity controls that will maintain the relative humidity in the region of 30-60%.[5]

It has been common knowledge for many years that increased partial pressures of nitrogen in the breathing gas at depths greater than 100 feet or so give rise to a condition called "nitrogen narcosis" or "rapture of the deep".[59, 88] As the depth increases, the narcosis deepens and intellectual and motor efficiency steadily decline.[60, 62] Behavioural changes characterized by euphoria and neuromuscular incoordination are common,[61] and the condition has been likened to alcohol intoxication. Another hazard develops as a diver descends to greater depths; i.e. as the pressure increases, the density of the breathing mixture also increases, resulting in an alteration of his ventilatory pattern.[38, 63] More effort is required to ventilate his lungs, and hence ventilatory efficiency decreases—particularly when the diver is working hard under great ambient pressure. These conditions can lead to respiratory fatigue, carbon-dioxide autointoxication, and increased susceptibility to both nitrogen narcosis and oxygen toxicity.[38, 39, 64] For these reasons, compressed air, or atmospheres with high percentages of nitrogen, are not used in prolonged deep saturation diving. Animal studies have also indicated that the use of compressed air for deep saturation diving is dangerous.[65] Shallow saturation dives carried out in 1963 by Cousteau[49] at 33 feet under the Red Sea were not affected by these characteristics of nitrogen under pressure.

Helium has been used in all recent deep open-sea diving experiments because at current experimental pressures it is not associated with any measurable narcosis or significantly decreased performance[62, 66-68] (Fig. 6). However, as these experiments are conducted at greater and greater pressures, these undesirable effects may become important,[90] particularly limitations of pulmonary ventilation.[38, 62, 69] Current deep underwater dwellings usually contain only a small amount of the original residual nitrogen, and helium is used as the oxygen diluent. The use of helium as the inert gas gives rise to other unique problems. Helium has very high thermal conductivity (nearly six times that of nitrogen) and this property, combined with the increased molecular availability as depth increases, chills the diver rapidly.[1, 5, 9] This effect in the synthetic gaseous environment increases with depth, and each dwelling must have a powerful and reliable source of heat to protect the divers. Recent deep saturation dives have required habitation temperatures between 82 and 86° F.[1, 9, 55] Another unique difficulty in the use of helium is that voice communication breaks down, owing to a multiplicity of factors; in the helium-oxygen atmosphere, the diver's voice is high-pitched and unintelligible both to himself and to the crew topside.[1, 70] Under these circumstances, the listener is subject to "a confusion of cues"—a potential hazard if information, passing between divers and the crew topside, is misinterpreted, particularly in an operational emergency. Efficient voice communications in helium is the subject of much intensive current research.[5, 70]

Few attempts have been made to use other gases such as hydrogen[71] and neon[62] and to evaluate them with respect to such critical factors as narcosis, ventilation, voice communication and decompression. So far no open-sea saturation dives have been made using these gases. Hydrogen is particularly

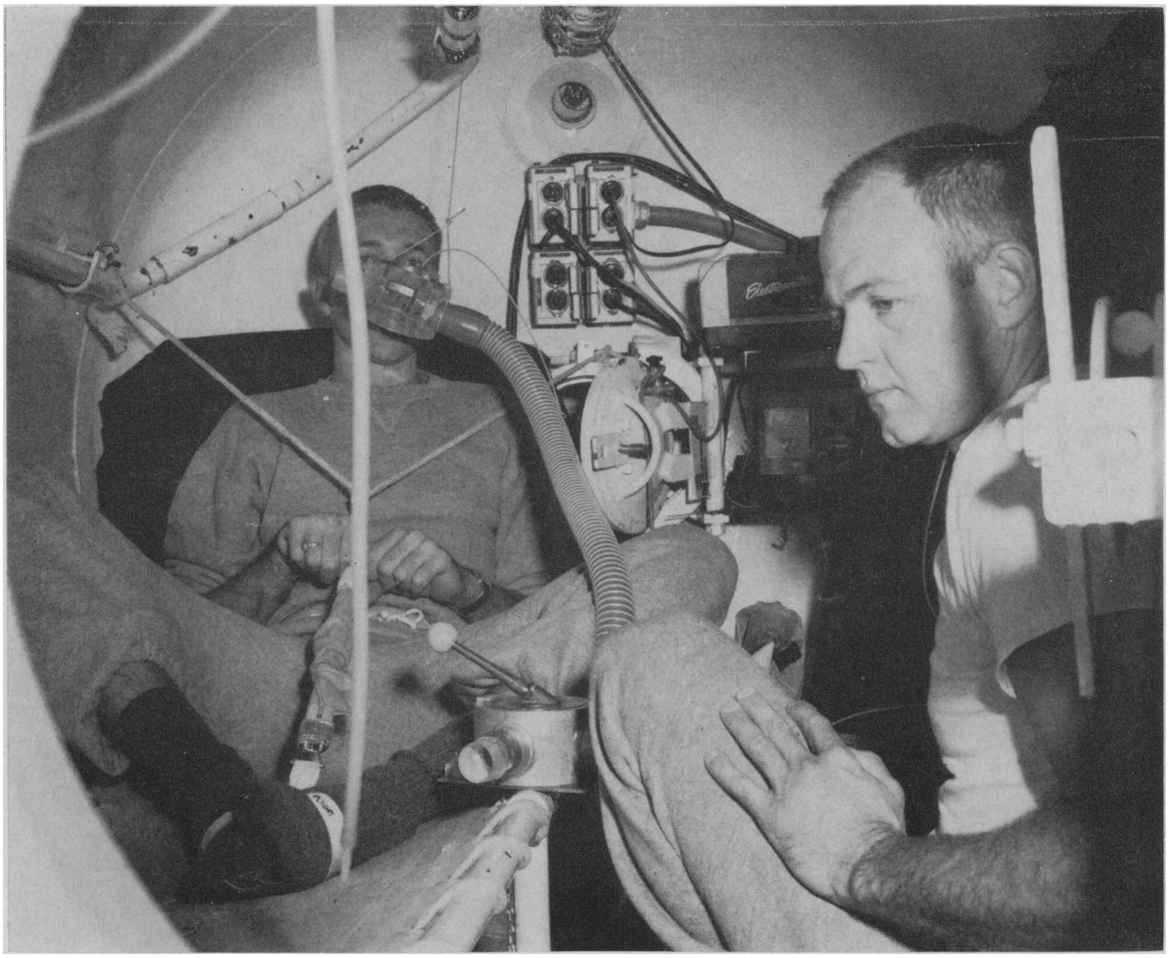

Fig. 6.—Two Ocean Systems, Inc. divers carry out oxygen consumption tests under 20 atmospheres of helium pressure in a research chamber in Tonawanda, N.Y. Both men remained at this pressure (equivalent to 650 feet of sea-water) for two days carrying out many experiments including exercise tolerance and CO_2 response tests, and demonstrating man's effectiveness at this depth. (Photograph—Linde Division of Union Carbide Corp.)

difficult to handle because of its explosive characteristics when it is mixed in uncontrolled combinations with oxygen. However, in recent work carried out by Ocean Systems, Inc., a neon-oxygen mixture was breathed by two divers for 30 minutes at 650 feet without measurable narcosis or decrease in psychomotor efficiency.[72]

OTHER IMPORTANT POTENTIAL PROBLEMS

Compression

As the diver descends, or is compressed in a chamber, he must ensure that the gas pressure in his body cavities, such as the lungs and sinuses, is kept equal to the increasing ambient pressure. If the pressure increase is not equalized, a relative vacuum occurs, and edema and bleeding into the cavity results. Failure to equalize, unsatisfactory chamber gas mixing and turbulence, and the heat of chamber compression are among the hazards facing the diver during compression.[55] These hazards are most likely to be encountered in a chamber that is being rapidly pressurized to some equivalent sea-water depth. If the diver is unable to "equalize" his sinuses and middle ears to the increasing ambient pressure, he inevitably suffers pain and tissue damage.[14-17] If compression is too rapid, he may become hypoxic because oxygen does not mix efficiently with the inert gas. Fortunately the diver carried to the continental shelf in his submersible decompression chamber is in a well-controlled compression situation. Also, saturation divers are not routinely compressed rapidly, and these problems rarely arise.[1, 5, 55]

Decompression—Uncontrolled and Controlled

Once a diver's blood and tissues are saturated with inert gas during his residence deep in the sea, a sudden return to the surface pressure will almost certainly be fatal. In order to avoid the irreversible effects of decompression that would follow flooding, fire, or other reasons for emergency escape from an undersea dwelling, readily available rescue chambers must be provided. These chambers must be easily accessible and autonomous, and contain the same respirable atmosphere as the dwelling.[73] Standby rescue chambers have been kept available on all undersea living experiments to date.[1, 5, 7, 9]

Exploration of undersea canyons or a steep edge of the continental shelf will require vertical excursion dives from the level of the undersea dwelling. Special care must be taken during any such dive carried out by a saturated diver. Recent work[74] indicates that such a diver may be capable of extensive downward excursions. However, it appears that upward excursions of more than about 30 feet above the dwelling may be dangerous. Vertical excursion dive limits will, of course, vary with the depth of saturation, but much intensive research still needs to be done to define these limits. In all probability, early research efforts will be directed at developing diving tables which will not require the diver to decompress before returning to the dwelling. As well, it will be important to develop tables that will allow effective undersea treatment of decompression sickness should it occur following vertical excursion dives. A conservative approach during initial undersea excursion dives is warranted, because the treatment of decompression sickness under these circumstances would be extremely difficult.

All laboratory and open-sea saturation dives to date have emphasized the critical control required during decompression[1, 5, 8, 9, 65, 75, 76, 87] that, in one dive, lasted as long as six days.[55] This control is necessary to prevent the formation of inert gas "bubbles" in the tissues and blood stream, which most workers believe is responsible for decompression sickness. Decompression sickness occurring at great depths creates an extremely difficult medical problem.[77] Not only is a definitive diagnosis difficult, but the treatment procedure is long and complicated. A serious episode demands that the physician join his patient by compressing to the required depth. In any event the diver must be recompressed to a depth that will give relief as soon as possible. Additional therapeutic steps, such as increasing the PO_2 or intravenous fluids, are taken according to the severity of the problem. Most cases of decompression sickness have been treated in deck decompression chambers, which calls for a high degree of skill and co-ordination between the divers and the topside "life-support" team.

In recent open-sea experiments linear rates of ascent in the range of about 10-12 min./foot have been used successfully.[1, 5, 9] Breathing 100% oxygen during the latter stages of this type of decompression has been added to diminish the possibility of decompression sickness.[1]

Fire

The introduction of oxygen at high partial pressures into a closed chamber creates a potential hazard of explosion and fire unless sources of ignition and combustion are strictly eliminated and the oxygen is vented out of the chamber.[78-82] A fire in an underwater or surface chamber is extremely dangerous because of the rapid build-up of heat and toxic fumes, and because, before the divers can escape from their confinement, they must undergo a long period of decompression.

Electrocution

The high electrical conductivity of sea-water increases the possibility of electrocution—particularly if high-voltage power tools and welding equipment are improperly used. However, keeping the voltage at electrical outlets as low as possible, and adhering to rigid engineering codes and safe diving procedures, minimizes the risk of electrocution.[83]

Problems Arising from Human Factors

Any review of medical problems that may occur during a prolonged deep saturation dive should include those brought to the dive situation by the diver himself. There is no question that, at present, prolonged deep diving represents potentially serious psychological stress. Past experience, particularly in manned space research, has shown that any such stress, if sustained, can, and probably will, enhance latent psychological or physiological defects. In addition to the more obvious forms of stress, the free diver suffers a diminution in the effectiveness of almost all his senses. Vision, hearing, touch, smell and body orientation are more or less altered according to water conditions.[6, 22] Also the diver's underwater efficiency is handicapped by the fact that, to date, there is still no effective deep underwater communication between divers, or between divers and topside.[84] The saturated diver is in a condition of partial sensory isolation. It is evident, then, that candidates for this type of work must be thoroughly screened by extensive medical and diving histories, and physical and special examinations.[55] Also, only the most experienced divers can qualify for the deeper saturation dives. The ideal candidate is one with a quiet, relaxed disposition, a specialist in some underwater activity which will contribute to the mission's success, and he must have extensive diving experience.

A diver working for long periods at great depths must be in excellent physical condition.[85] The reasons for this are obvious. If a diver's physical condition is inadequate, any stress such as oxygen toxicity or decompression sickness will have a far greater effect. As well, while under water, the diver may encounter an emergency situation that will demand sustained exertion in order to save his life. Even well-conditioned divers are fatigued after a a prolonged pressure exposure.[8, 50, 55] Individuals with cardiopulmonary, neurologic, and ear, nose and throat pathology should be disqualified from any kind of diving—particularly saturation diving. The list of other disqualifying conditions is extensive, and has been reported elsewhere.[14-19]

It is important to recognize that the duration of current undersea-living experiments is increasing; for example, Carpenter remained submerged last summer for 30 days at 205 feet.[9] Therefore, "non-diving" medical problems will probably increase. In our recent laboratory work, during pressure exposures of many days' duration, we treated complaints such as headaches, skin infections, and head colds. On one dive it was extremely difficult to make a differential diagnosis in a diver with acute vertigo and vomiting. Incidents such as this emphasize that all laboratory and open-sea saturation research dives should be carried out under medical supervision, with a diving physician present at all times during and for some time after the pressure exposure.[1, 55] He must have at his command adequate drugs, emergency equipment, and procedures to treat successfully any diving problem. Also, he must be prepared to be "compressed" to the depth at which the medical emergency has occurred in order to treat the diver under pressure. After he has carried out the treatment, the physician may have to undergo decompression.[55]

It is recognized that there is great variation among individuals in their susceptibility to various diving diseases, both physiological and psychological. For example, one "decompression schedule"* may be suitable for a large number of divers, while under this exact schedule another diver may suffer decompression sickness.[86] This variation also applies to other hazards such as oxygen toxicity,[39] and to a diver's response and adaptation to any intensely threatening situation. Individual variation has also been noticed in symptoms of musculoskeletal discomfort encountered while at depths usually greater than 200 feet; this discomfort usually manifests itself as a slight "soreness" of the wrists and larger joints.[55] There will probably also be great variation in an individual's day-to-day and diurnal responses to the stresses of prolonged residence under the sea.

As the duration of prolonged deep diving is extended into weeks and months, the diver's psychological health will become increasingly important. It is unlikely, however, that such psychological problems will represent real dangers in the underwater environment, although some adjustment will be required for long-term stays.[9]

Despite possible antagonistic and synergistic effects from the interaction of the multiple potential stress factors on the deep-dwelling diver, man again appears to be proving his adaptability to unusual environments. To date no significant subjective or measurable decrease in performance has been observed in divers under conditions of prolonged residence in high pressures.[1, 7, 9, 66] Although much work remains to be done, there does not appear to be any insurmountable barrier to human occupation of the world's continental shelves.

*A "decompression schedule" is a detailed program of the third phase of a dive profile. It describes the depths and rates at which decompression should proceed, and gives additional information such as the breathing of specific gas mixtures at specific depths.

Summary and Conclusions

I have outlined some of the most important of the potential medical and performance problems inherent in man's current attempts to dwell for long periods deep beneath the sea. This is not an all-inclusive list. Some of these problems cannot be predicted and will appear when we dive deeper and longer. In addition, the degree of interaction and the long-term effects of the various types of stress remain to be ascertained and will be the subjects of future intensive investigation, both in the laboratory and under the sea.

Living under the sea, which is much more efficient than previous modes of diving, has taken on great scientific, military and economic importance. Undersea living depends on the combined efforts of physicians, biologists, physiologists, chemists, mathematicians, and ocean engineers. From the last group comes guidance in the design of the vital, life-support equipment necessary to achieve the maximum in long-term diver performance and safety, with minimum hazard.

Fortunately, up to the present, serious medical problems, while living under the sea, have been rare. More important, none of the recognized medical or performance problems appear insurmountable, at least at continental shelf depths.

To surmount existing obstacles and hazards, man will first have to extend cautiously his ability to live under the sea. Then, as he has in all his previous exploratory endeavours, he will proceed into the depths with great authority.

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